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LIQUID TRANSPORT ACROSS FABRIC LAYERS

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Rita M. Crow and Malcolm M. Dewar

DEFENCE RESEARCH ESTABLISHMENT OTTAWA
REPORT NO. 1002

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ABSTRACT

This paper shows qualitatively that for a fabric to wick water from one layer to another, the dry fabric layer must have a certain hydrophilicity to attract the water out of the wet layer. Some of the water that a fabric takes up is contained among its fibers and is a function of how many fibers the fabric has in its yarns and how many yarns per unit volume the fabric has. Water is also contained in the yarn interstices. For conventional textile fabrics, water will move from the inter-fiber and inter-yarn pores of the wet fabric into those of the initially-dry similar fabric until an equilibrium is established between the two layers. This equilibrium is reached when sufficient water has entered the dry fabric such that the water bridges the spaces among the fibers. The dry layer will stop accepting water when its inter-fiber pore and inter-yarn pores of equivalent size are full. CANADA. (JES)

RESUME

Ce rapport montre de façon qualitative que, pour qu'un tissu sec imbibe de l,eau d,une couche de tissu mouillée adjacente, il doit avoir une qualité hydrophile pour attirer l,eau du tissu mouillé. Une partie de l'eau qu'un tissu absorbe est contenue parmi ses fibres et est fonction du nombre de fibres dans les fils du tissu ainsi que du nombre de fils par unité de volume dans le tissu. L'eau est également retenue dans les interstices du tissu. Pour des tissus conventionels, l'eau se déplacera des fibres et fils mouillés au tissu sec, jusqu'à ce qu'un équilibre soit atteint entre les deux couches. Cet équilibre est atteint lorsque suffisament d'eau soit entré dans le tissu sec pour que ses interstices, ou pores, soient remplies d'eau. La couche initialement sèche, cessera alors d'absorber l'eau.

EXECUTIVE SUMMARY

This study examined the wicking of water from one layer of fabric to another both qualitatively and quantitatively. The wettability of a series of fabrics was determined and related to whether or not wicking occurred from a wet, bottom fabric to a similar dry, upper fabric. It was found that the popularly-held view that fibers with high regains are hydrophilic and vice versa is not always true. Hydrophilic finishes make low regain hydrophobic fibers hydrophilic. It was shown qualitatively that for a fabric to wick water from layer to another, the dry fabric layer must have a certain hydrophilicity to attract the water out of the wet layer and that the wet layer must contain sufficient water to be able to donate some to the upper layer.

It was found that the total amount of water a fabric takes up varies from fabric to fabric. Some of the water that a fabric takes up is contained among its fibers and is a function of how many fibers the fabric has in its yarns and how many yarns per unit volume the fabric has. A simple calculation determined that some of the water must also be contained in the yarn interstices. It was concluded that water will move from the inter-fiber and inter-yarn pores of the wet fabric into those of the initially-dry similar fabric until an equilibrium is established between the two layers. It is proposed that this equilibrium is reached when sufficient water has entered the dry fabric such that the water bridges the spaces among the fibers. The dry layer will stop accepting water from a re-wetted bottom layer when its inter-fiber pore and inter-yarn pores of equivalent size are full.

INTRODUCTION

The movement of water from one fabric layer to another has once again gained interest recently due to the introduction onto the market of fibers and fabrics which, when worn next to the skin, are claimed to move perspiration from the skin to the next clothing layer, thus keeping the wearer dry and comfortable. The mechanism by which this occurs is not fully understood. Several workers have carried out experiments on this subject, the majority concluding that there has to be a minimum amount of moisture in the wet fabric before capillary wicking from the wet layer to a dry one will take place [1,7]. Spencer-Smith [7] found this amount to be 70 to 80% above regain for hygroscopic, woven linen fabrics. Adler and Walsh [1] found that wicking between two layers of woven cotton occurs at 122% above regain and that knitted fabrics did not wick. Miller and his coworkers [4,5,6] have examined the transfer of a liquid drop through layers of fabrics and found quantitatively that, with time, the penetration of the liquid depends on wettability and pore size of the fabrics, with the liquid accumulating in the fabric which is more wettable and has smaller pores. This paper examines the transport of water from one fabric layer to another and explains qualitatively the mechanism by which it takes place.

EXPERIMENTAL PROCEDURE

Fifty-eight fabrics were obtained from Testfabrics Incorporated, Middlesex, N.J.. The selection included both woven and knitted fabrics made from acrylic, cotton, nylon, polyester and wool and woven fabrics made from linen, fiberglass, polypropylene and silk.

To determine the wettability of the fabrics, a range of solutions were made up with varying surface tensions, from 82 mN/m for a 25% salt and water mixture, to water and 10% incremental steps of water/methanol mixtures ending with 100% methanol solution having a surface tension of 22.7 mN/m. Snippets of the fabrics were gently placed on the various liquid surfaces and it was noted whether they either sank quickly or floated. (There were a few exception where the fabrics floated briefly before sinking.) It was considered that a fabric's approximate equivalent critical surface tension was indicated by the highest surface tension of the liquid which would permit the snippet to sink. The higher the equivalent critical surface tension, the more wettable the fabric is. This method is similar to that described by others [2,8].

Initially, in order to determine whether a fabric would wick from layer-to-layer, a dry swatch of each fabric was placed on a wet, non-dripping, pigmented swatch of the same fabric and it was noted whether or not there was wetting of the upper, dry swatch. The transfer of the blue pigment (Cinquasia Blue) with the water indicated that liquid transfer was by capillary wicking rather than diffusion. This was confirmed in experiments where the fabric layers were weighed periodically. If no dye was transferred to the dry fabric, its increase in mass over an hour was of the order of 1 to 8%. When dye was transferred to the dry fabric, the increase in mass of the dry fabric was substantial and occurred within the first few minutes.

For the qualitative layer-to-layer experiments, 70 mm diameter specimens were cut from 6 fabrics which did wick from layer to layer. Their description is given in Table 1. Two or three specimens were weighed and one wetted in distilled water containing the blue pigment and re-weighed. The swatches were placed on top of an inverted 90 mm diameter plastic petri dish with the wet swatch on the bottom. They were covered with a second inverted petri dish weighing about 7 to 8g. This allowed some light and constant pressure on the layers and limited evaporation of water from the system. All specimens were weighed at intervals until no more increase in mass was measured. The percent water which went into the dry layer is reported as "Minimum into Dry Layer" in Table 2. "Remaining in Wet" is the water remaining in the wet specimen after this experiment. Further experiments were done where the wet layer was rewetted several times until the upper "dry" layer would pick up no more water, "Maximum into Dry Layer". To wet out a specimen, it was held by tweezers, immersed in the liquid and then each side of the speciment was briefly patted on paper towelling. This removed sufficient water from the fabric surface so that none was transferred to the petri dish surface. The reproducibility of the amount of liquid picked up by the wet specimens was excellent for all fabrics, except the very fine tricot, 122, as can be seen by the low coefficients of variation (cv) for "Maximum into Wet" in Table 2.

The amount of liquid held in the variously-sized pores of the selected fabrics was determined using the apparatus and method described by Miller and Tyomkin [6]. The method is essentially a liquid extrusion process and involves the "gravimetric monitoring of water as it drains from an initially saturated sample as increases in pressure gradient are applied across it". The liquid used was distilled water with a measured surface tension of 72 mN/m. The surface tension of the water was measured after each experiment and was found to be greatly reduced (46 to 53 mN/m) because the hydrophilic finishes on the fabrics had dissolved into it. The lower, measured, surface tension values were used in the calculations of pore sizes of the fabrics. It is appreciated that this is not an ideal methodology. The alternative is to scour the fabrics. However, when this was done, the fabrics had become so hydrophobic that they would not wick from layer-to-layer. Further, it is not known how the removal of the hydrophilic finishes would affect the capillary-filling capacity of the fabrics in the pore-size determination experiments. Thus it was decided to use the fabrics as received.

TABLE 1

Pertinent Physical Properties of the Selected Fabrics

Test Fabric Number	Fiber	Description	Mass g/m²	Thickness mm	Count	% Fiber Volume	% Regain	Critical Surface Tension (mN/m)
122	Acetate	tricot knit	69	0.28	11x16	19	5.4	59-73
154	Acetate	plain weave	168	0.46	16x12	28	5.8	38-49
755	Polyester	plain weave	184	0.50	34x24	26	0.6	38-43
443	Cotton	double knit	244	1.65	9x13	14	7.2	49-59
466	Cotton	lain weave	328	0.58	21x17	37	8.5	73-83
652	Silk	noil plain weave	139	0.56	21x20	32	9.7	30-33

TABLE 2

Percent of Water Held In Fabrics[1] and Corresponding Pore Sizes

		Fabric Designation						
		122	154	755	443	466	652	Mean
Maximum held by Wet Layer	$\bar{x}$	110	114	164	277	80		
	cv	30	5	3	10	0	9	
	n	3	5	3	4	2	3	
Pore Size (μ)		5.8	6.7	7.6	5.8	4.4	4.3	5.8
Maximum Into Dry Layer	$\bar{x}$	99	82	85	200	62		
	cv	28	2	3	7	10	10	
	n	3	7	3	3	3	3	
Pore Size (μ)		4.5	4.1	3.9	3.2	2.7	2.7	3.5
Minimum Into Dry Layer	$\bar{x}$	43	42	50	108	25	69	
	cv	5	13	8	1	1	10	
	n	3	5	4	3	2	4	
Pore Size (μ)		3.0	2.1	2.4	1.9	1.2	1.5	2.0
Remaining in Wet Layer	$\bar{x}$	51	65	54	128	43		
	cv	2	25	0	1	1	8	
	n	2	5	3	2	2	3	
Pore Size (μ)		3.4	3.2	2.5	2.2	2.1	2.1	2.6
At Breakaway		65	83	59	224	61	169	
Pore Size (μ)		4.3	4.1	2.7	3.9	2.9	3.5	

[1] This is expressed as $\frac{(M - Mc)}{Mc} \times 100$
where Mc is the mass of the conditioned fabric and M is the mass o[illegible]er and the fabric.

RESULTS AND DISCUSSION

A plot of the willingness of the fabrics to wick to a second, similar layer versus its critical surface tension (CST) is given in Figures 1a and 1b. The fabrics which had CSTs higher than that of water wicked instanteously. Those with lower CSTs wicked into the second layer within about 5 minutes. Those with even lower CSTs wicked into the second layer in circles or crosses, the more hydrophilic fabrics wicking in circles, the less so in crosses. This behaviour is shown in Figure 2. Crosses occur when wicking is along yarns with little transfer from warp to weft or vice versa. Those with low CSTs did not wick at all from layer to layer. In many instances, this was because the "wet" fabric was so water-repellent, it would not wet out.

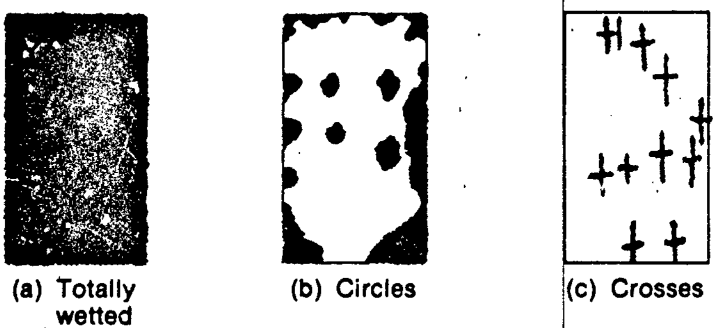

Figure 2: Wicking patterns into a dry upper fabric from a wet, lower, similar fabric. (a) Totally wet. (b) Circles. (c) Crosses.

These results dispel the conventional idea that fibers with high regains, such as the natural fibers, are hydrophilic and those with low regains, such as polyester, are hydrophobic. The wools in this study were all very hydrophobic. One polyester was very hydrophilic and some cottons were very hydrophobic. Hydrophilic finishes can make hydrophobic fibres hydrophilic, but as mentioned above, these finishes can be easily dissolved in water and are removed from the fabric. In related work on vertical wicking, it was observed that when strips of hydrophobic fabrics with high regains were hung in water for some length of time, the water eventually wicked up the fabric. It is presumed that a monolayer of water accumulates on the surface of such fibres, turning the hydrophobic surface into a hydrophilic one.

Typical results for the layer-to-layer wicking behaviour are shown in Figures 3a and 3b. As Spencer-Smith [7], we found that as the amount of liquid in the wet layer increased, so did the amount of liquid which

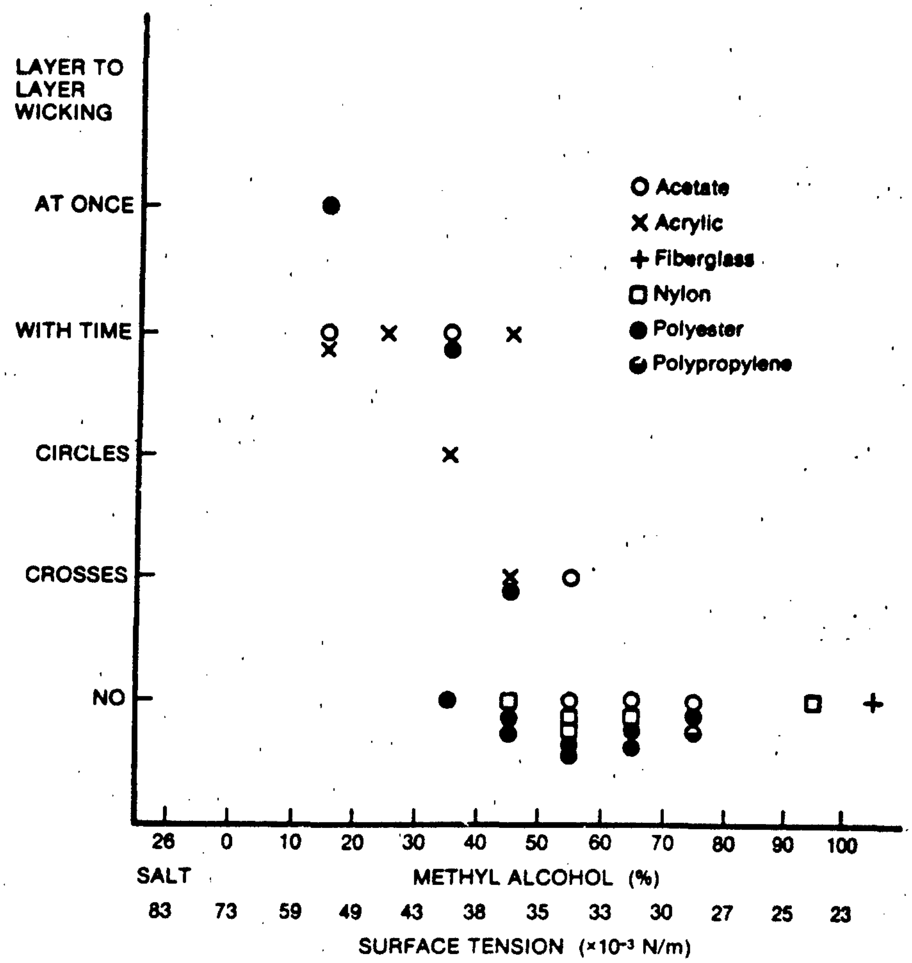

Figure 1a: Fabric layer wickability versus surface tension for low regain, synthetic fibers.

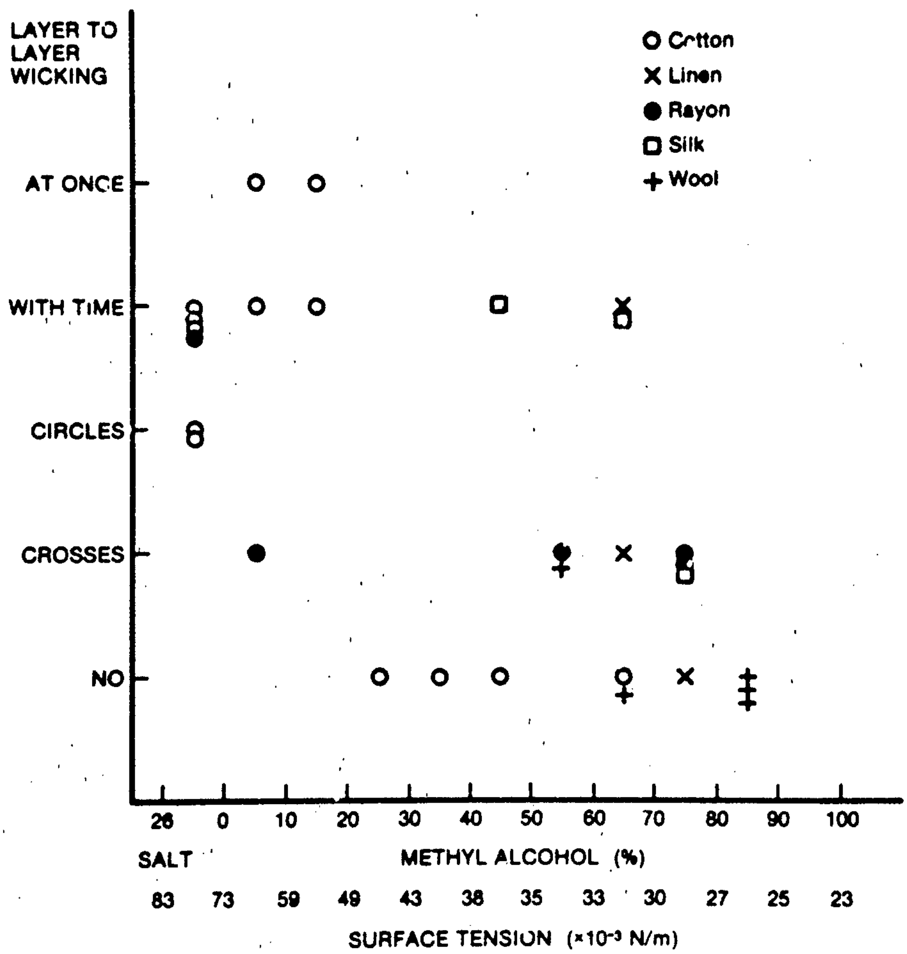

Figure 1b: Fabric layer wickability versus surface tension for high regain fibers.

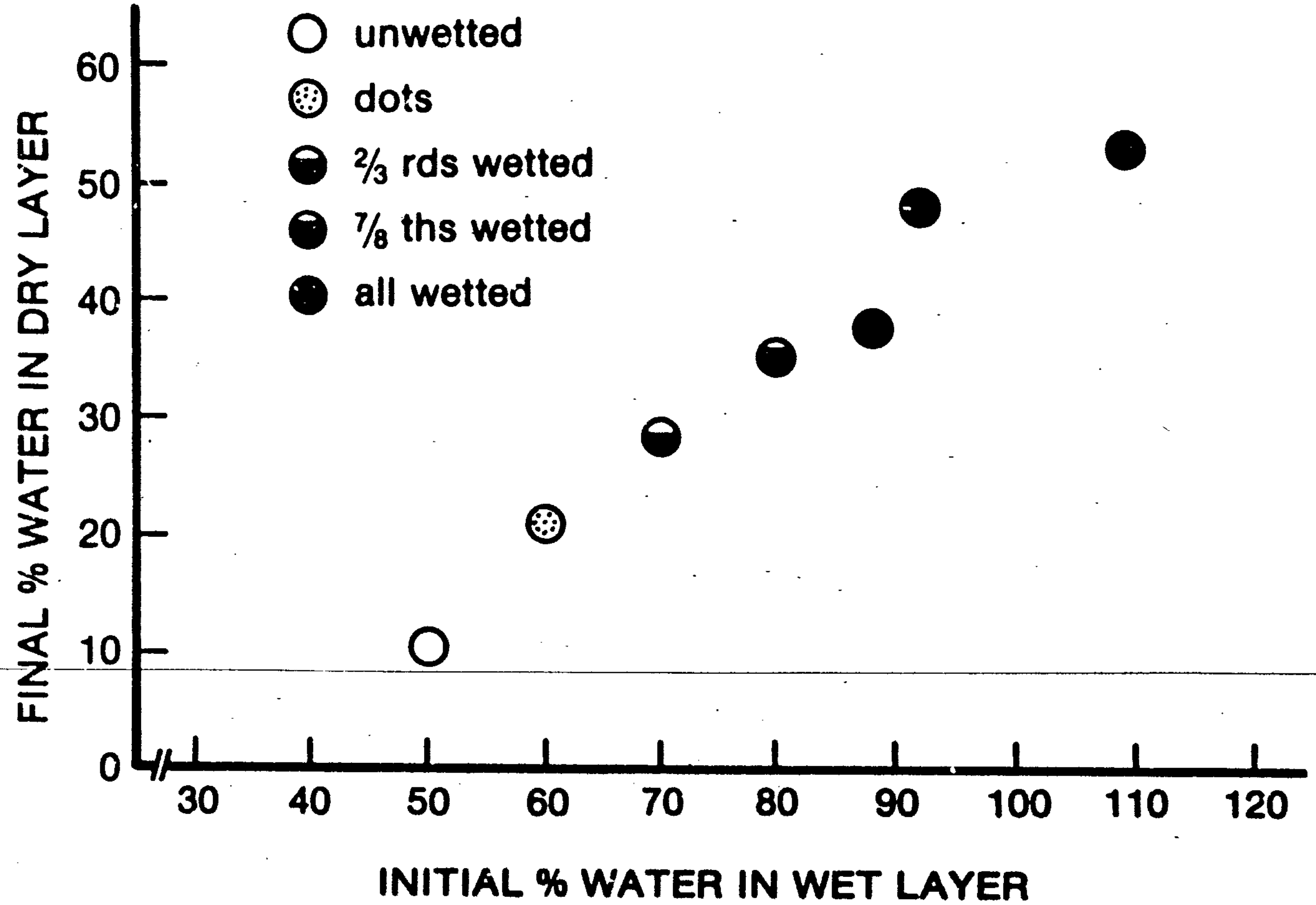

Figure 3a: Typical layer-to-layer plot (Fabric 122).

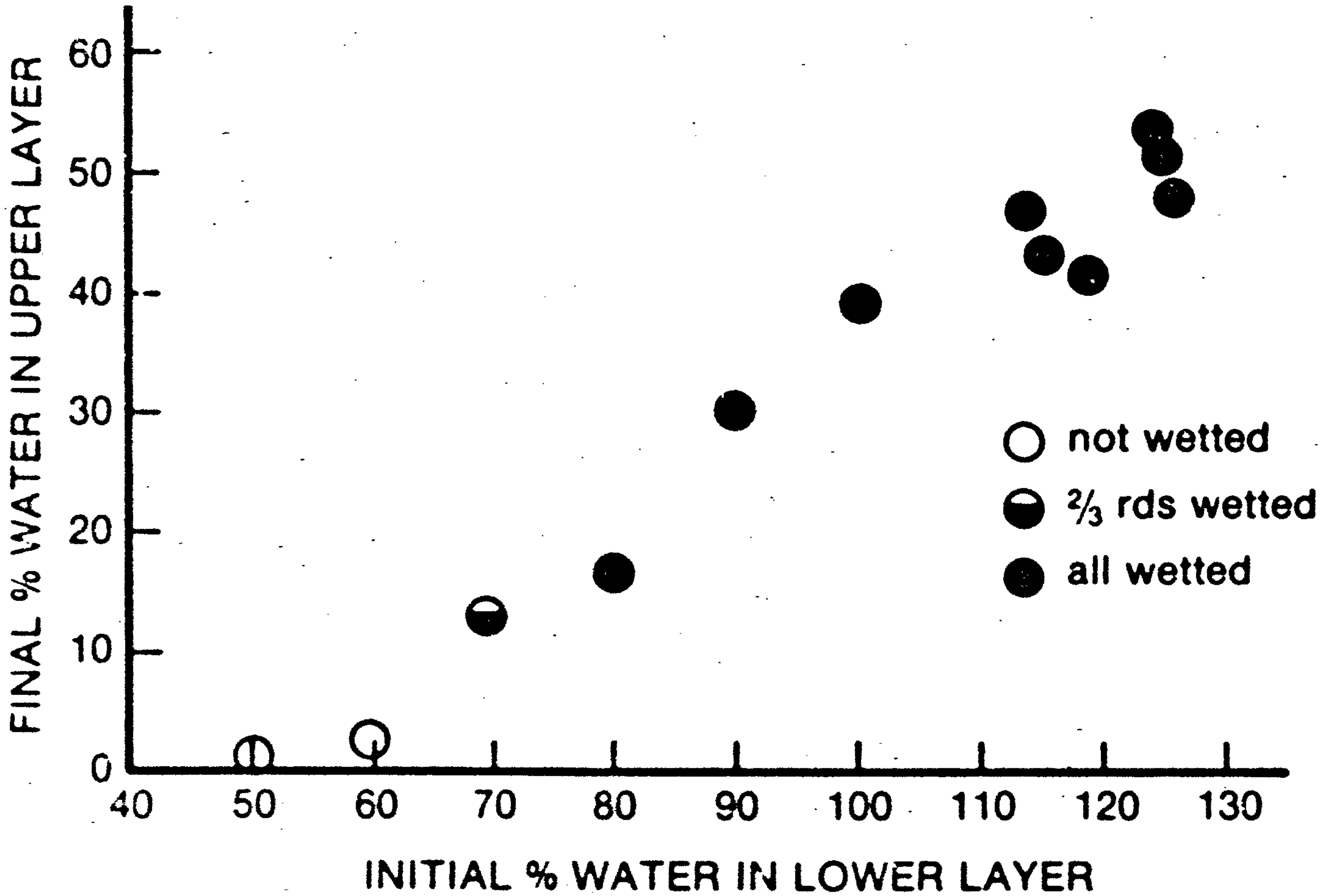

Figure 5b: Typical layer-to-layer plot (Fabric 755)

wicked into the dry layer to a limit when no more liquid wicked from the wet to the dry layer. The consistency of results, unusual for textiles, led us to believe that this was an emptying - filling phenomenon, i.e., that wicking occurs from the large pores of the wet layer to the small pores of the dry layer.

The amounts of water left in the dry and wet layers under various conditions as well as the pore sizes at which these occur are given in Table 2. It is assumed that water fills the finest pores first. The pore size value therefore represents the diameters of the largest-filled pores. "At breakaway" refers to the amount of water remaining in the fabric at the end of the pore-size determination experiment when the fabric and filter paper under it no longer could sustain the pressure gradient across them and the water "broke away". In order to estimate the pore sizes at other water contents below breakaway, a plot was made of pore size versus amount of water in the fabric using the values of "at breakaway", at wet fabric saturation and the origin. The pore size at the corresponding percent water was read from this line.

It can be seen that the percentage and so the actual amount of water that can be picked up by wicking by a specimen varies from fabric to fabric and is not a fixed percentage as other workers have found [1,7]. This is probably because the fabrics used in this study represent a wider range of fabric/fiber types and wetting properties. Other workers have expressed their results in terms of "above regain". It is considered that subtracting the regain from the present results would not accomplish much since the regains are so small in comparison to the amounts of water held by the fabrics.

As it can be seen in Table 2, the common factor governing the amount of water held in the fabric is the pore size. The maximum amount of water held by the fabric is in the pores of about 5.8μ and less. If the fibre diameters are assumed to be about 15μ and the fibres within the yarns packed hexagonally as in Figure 4a, then the diameter of the largest circle which can be inscribed in the triangular space between the yarns is 5.5 μ which is in good agreement with the experimental result. Thus it would appear that the majority of water that a fabric takes up is contained among its fibers and is a function of how many fibers the fabric has in its yarns and how many yarns per unit volume the fabric has. This water would exist in a pendular state as described by Luikov [3] and shown in Figure 4b.

The funicular state described by Luikov is illustrated in Figure 4c and to its first approximation in Figure 4d. It is proposed that this is the steady state when a dry fabric wicks from atop a wet, saturated one. The water from the wet fabric goes into the dry fabric until a circle is formed in the cross-sectional triangle among the fibers of the wet fabric. Since work is required to "break" the circle and the system does not have this energy, water ceases to flow out of the wet fabric. Conversely, the dry fabric will accept water until the "corners" of the triangle are full and just join up.

In reality, the fibers are not tightly packed in the yarn as illustrated in Figure 4a, the cotton fibers are not circular, the capillaries among the fibers are not straight or circular and the "hole"

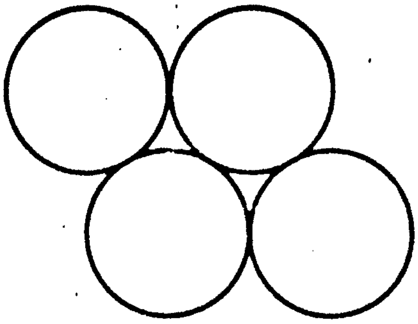

Figure 4a: Hexagonal packing of fibers.

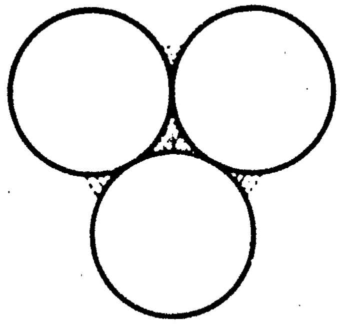

Figure 4b: Pendular state of water.

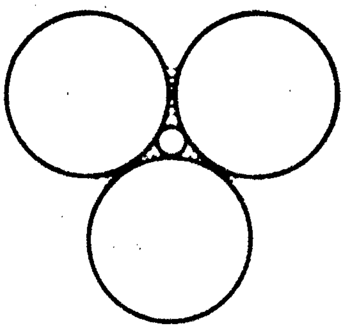

Figure 4c: Funicular state of water.

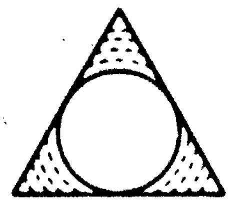

Figure 4d. First approximation of the funicular state.

among the fibers may not be a circle. If it is assumed that there is some space among the fibers, then the idealized case is shown in Figure 5.

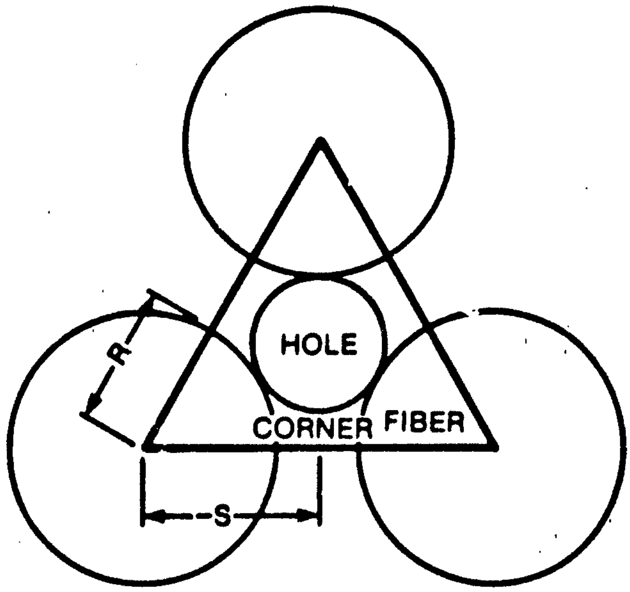

Figure 5: Idealized case of fiber packing.

If R is the radius of the fibers and 2S the distance between their centers, then the area of the space between the fibers, i.e. the corners and the holes, is and the radius of the hole among the fibers is

$$\sqrt{3}\ S^2 - \frac{\pi}{2} R^2 \tag{1}$$

and the radius of the hole among the fibers is

$$\frac{2S}{\sqrt{3}} - R \tag{2}$$

If the whole space among the fibers is filled with water (i.e. the maximum water held in a layer), then the percent by mass of water in the fabric is given by the expression

$$\frac{\sqrt{3}\ S^2 - \frac{\pi}{2}\ R^2}{\frac{\pi}{2} \cdot R^2\ \rho} \times 100 \tag{3}$$

where ρ is the specific gravity of the fiber.

Likewise, the minimum water held in a layer where the water is in the corners, is

$$\frac{\sqrt{3}\ S^2 - \frac{\pi}{2} R^2 - \pi \left(2 \frac{S}{\sqrt{3}} - R\right)^2}{\frac{\pi}{2} \cdot R^2\ \rho} \times 100 \tag{4}$$

Table 3 shows these minimum and maximum percentages of the mass of water to fiber held at various ratios of S and R. Extracted from Table 2 are the experimentally-found ratios, these being similar for the dry and wet layers, i.e. .49 and .50. These experimental results show that the spacing among the fibers is at a S/R of 1.2. The diameter of the hole at this spacing would be 5.8μ which is the mean diameter of the six fabrics. The ratio of the area of the "hole" to the area of the "hole plus the corners" among the fibers is .49, confirming the emptying-filling phenomenon and the theory that water does go into the initially-dry fabric until a "hole" is formed among the fibers. However, if one calculates the amount of water held in yarns with S/R = 1.2, there is not sufficient water to account for all the water held by the totally-wet fabric. Obviously water is being held elsewhere and an obvious place is at the yarn interstices to an equivalent pore size of 5.8μ. However, there is no correlation between thread count and the amount of water held by a fabric, but there is a good correlation between fabric thickness and the amount of water held by it. This is logical since the degree of contact at a yarn interstice is greater for thick yarns than for thinner yarns and so thick fabrics hold more water than thinner one. (It is noted that it is the doubleknit construction of 443 rather than its yarns which makes it so thick.)

The next question is why does the wet layer hold more water than its dry counterpart? Luikov's explanation [3] is that water rises higher in wet capillaries than in dry ones. However, there are other reasons because wetting a fabric by immersion is different from wetting it by capillary action. When a fabric is immersed in water, pores greater than 5.8μ among the yarns can be filled. Further all capillaries can be filled. When capillary wicking occurs into the dry fabric, only the inter-fiber and inter-yarn pores of 5.8μ and less will be filled with water. Additionally, it is possible that a few non-continuous pores in the "dry" fabric will never be filled. This results in the dry layer having a "pseudo" pore size of 3.5μ to be completely filled with water.

CONCLUSIONS

It is concluded that for wicking from one layer to another to occur, the dry fabric must have a certain hydrophilicity to attract the water out of the wet layer. Further, the wet layer must hold sufficient water to be able to donate water to the dry fabric. Some of the water that a fabric takes up is contained among its fibers and is a function of how many fibers the fabric has in its yarns and how many yarns per unit volume the fabric has. Water is also contained in the yarn interstices, the thicker the yarn, the more water held here. For conventional textile fabrics, water will move from the inter-fiber and inter-yarn pores of the wet fabric into those of the initially-dry similar fabric until an equilibrium is established between the two layers. This equilibrium is reached when sufficient water has entered the dry fabric such that the

TABLE 3

Percent of Water Held in Fabrics at Various Spacing/Fiber Diameter Ratios (S/R)[1]

Theoretical

S/R	Minimum	Maximum	Min/Max
1.0	5	10	.53
1.1	19	33	.56
1.2	29	59	.49
1.3	36	86	.42
1.4	40	116	.34

[1] This is expressed as a percent of the total mass of the fiber and the amount of water in the fabric.

Actual

	Mean[2]	cv (%)
Minimum into dry layer / Maximum into dry layer	.50	15
Remaining in wet layer / Maximum held by wet layer	.49	18
Minimum into dry layer / Maximum held by wet layer	.36	11
Maximum into dry layer / Maximum held by wet layer	.61	15

[2] is the mean of the ratios from each of the six fabrics

spaces or "corners" among the fibers just join up to form a circle in the center. The dry layer will stop accepting water when its inter-fiber pore and inter-yarn pores of equivalent size are full.

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REFERENCES

1. Adler, M.M. and Walsh, W.K., Mechanisms of Transient Moisture Transport Between Fabrics, Textile Res. J. 54, 334- 343, (1984).

2. B.O. Bateup, J.R. Cook, H.D. Feldtman and B.E. Fleischfresser, Wettability of Wool Fibers, Text. Res. J., 46, 10, pp 720-723, (1976).

3. Heat and Mass Transfer in Capillary-porous Bodies, 1st English ed., A.V. Luikov, Pergamon Press, New York, 1966, p212 -217.

4. Miller, B. and D.B. Clark, Liquid Transport Through Fabrics; Wetting and Steady-State Flow, Part I: A New Experimental Approach, Textile Res. J. 48, 150-155, 1978. Part II: Fabric Wetting, Textile Res. J., 48, 256-260, (1978).

5. Miller,B. and H.K. Perkins, Liquid Breakthrough in Multilayered Textile Structures, in "The International Nonwovens Technological Conference", June 2-5, 1986, Philadelphia, Pa.

6. Miller, B. and I. Tyomkin, An Extended Range Liquid Extrusion Method for Determining Pore Size Distributions, Textile Res. J. 56, 35 - 40 (1986)

7. Spencer-Smith, J.L., The Physical Basis of Clothing Comfort, Part 4, The Passage of Heat and Water Through Damp Clothing Assemblies. Clothing Res. J. 5, 116-128 (1977).

8. T.L. Ward and R.R. Benerito, Testing Based on Wettability to Differentiate Washed and Unwashed Cotton Fibers, Text. Res. J., 55, 1, pp 40-45, (1985).

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This paper shows qualitatively that for a fabric to wick water from one layer to another, the dry fabric layer must have a certain hydrophilicity to attract the water out of the wet layer. Some of the water that a fabric takes up is contained among its fibers and is a function of how many fibers the fabric has in its yarns and how many yarns per unit volume the fabric has. Water is also contained in the yarn interstices. For conventional textile fabrics, water will move from the inter-fiber and inter-yarn pores of the wet fabric into those of the initially-dry similar fabric until an equilibrium is established between the two layers. This equilibrium is reached when sufficient water has entered the dry fabric such that the water bridges the spaces among the fibers. The dry layer will stop accepting water when its inter-fiber pore and inter-yarn pores of equivalent size are full.

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